PLANETARY SYSTEM:
FROM GALILEO TO EXOPLANETS

Rosa M. Ros

Technical University of Catalonia, Barcelona (Spain)

Abstract

When in 1610 Galileo Galilei looked at Jupiter with the use of his telescope, he saw four "bodies" circling it (Figure 1). This discovery was in contradiction to the then generally held belief that all heavenly bodies turned round the Earth. This fact represented a scientific revolution at that time and helped in the acceptance of the Heliocentric Copernican System. As Jupiter and their Galilean satellites is a good model of a planetary system our intention is to study this using a set of photographs which we had taken previously.

When in 1995 Michael Mayor and Didier Queloz announced the detection of an exoplanet orbiting the ordinary main sequence star 51 Pegasi a new era began. Currently several methods are being used to find exoplanets more or less indirectly:

- Astrometry
- Radial velocity or Doppler method
- Pulsar timing
- Transit method
- Gravitational microlensing
- Circumstellar disks
- Eclipsing binary
- Orbital phase
- Polarimetry

Figure 1. Galileo observations

Each of these methods is more or less appropriated for different kinds of planets. For instance, it is possible to detect them by measuring the planet's influence on the motion of its parent star, but in this case the exoplanet found has to be very big. The smallest planets can be found eventually by observing the apparent luminosity variation in a star's as a planet passes in front of it, but this means that the observer must be approximately in the same plane as that of the planet's orbit. By using different methods it has been possible to list about 30 multiple-planet systems. We will compare them, in some way, with the solar system and the Galilean satellites of Jupiter.

A SMALL "PLANETARY SYSTEM" OBSERVED BY GALILEO

The set of photographs should be extensive enough taking into account the different behaviour of the satellites. To study Europe and Io motions we need some photographs

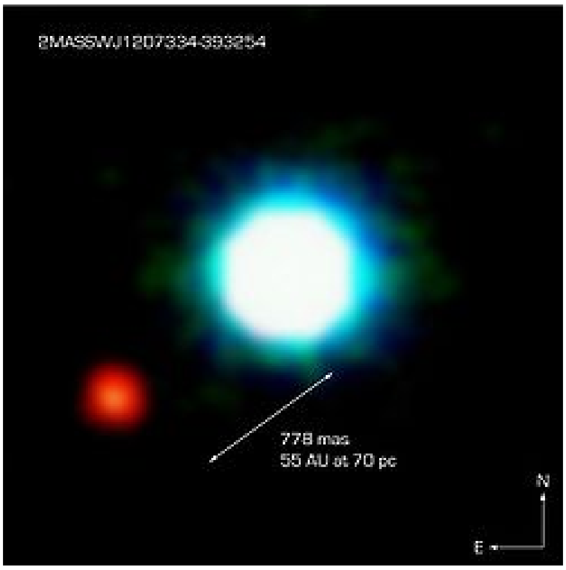

Figure 2. The first planet 2M1207b directly imaged. It has a mass 3.3 times Jupiter's mass and it orbits at 41 AU from the brown dwarf. In 2006, a dust disk was found around the parent star, providing evidence for a planet formation about the same as typical stars (ESO photo)

taken the same day at intervals of one hour; for Ganymede it is more convenient for us to take photographs every four or five days and finally for Callisto every eight days at least.

In this way in the set of photographs we can have some of them in which, respectively each one of the satellites appear in their furthest positions from the planet. The more accurate of the maximum position is also the final results are better, because one of our intentions is to calculate the parameters of the orbits of each one of the Galilean satellites.

In order to recognise each one of the satellites in a photograph, we need to use a computer programme which draws the relative positions of Jupiter and their Galilean satellites for one day and at specific times (Figure 3).

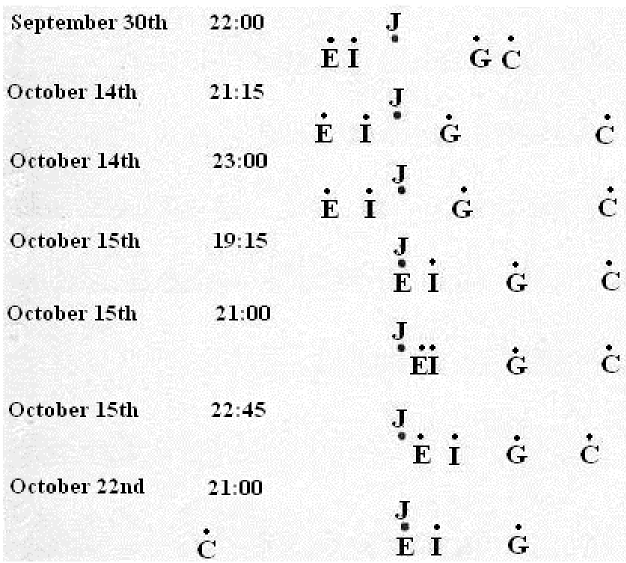

Figure 3. Computer simulation of Galilean Satellites in order to identify each one

We present in this paper a selection of photographs (Figure 4) for carrying out the proposed practice, because in each of them all the satellites appear in their furthest position. For each photograph, in Figure 3, there is the drawing made by the computer that allows us to identify the satellites.

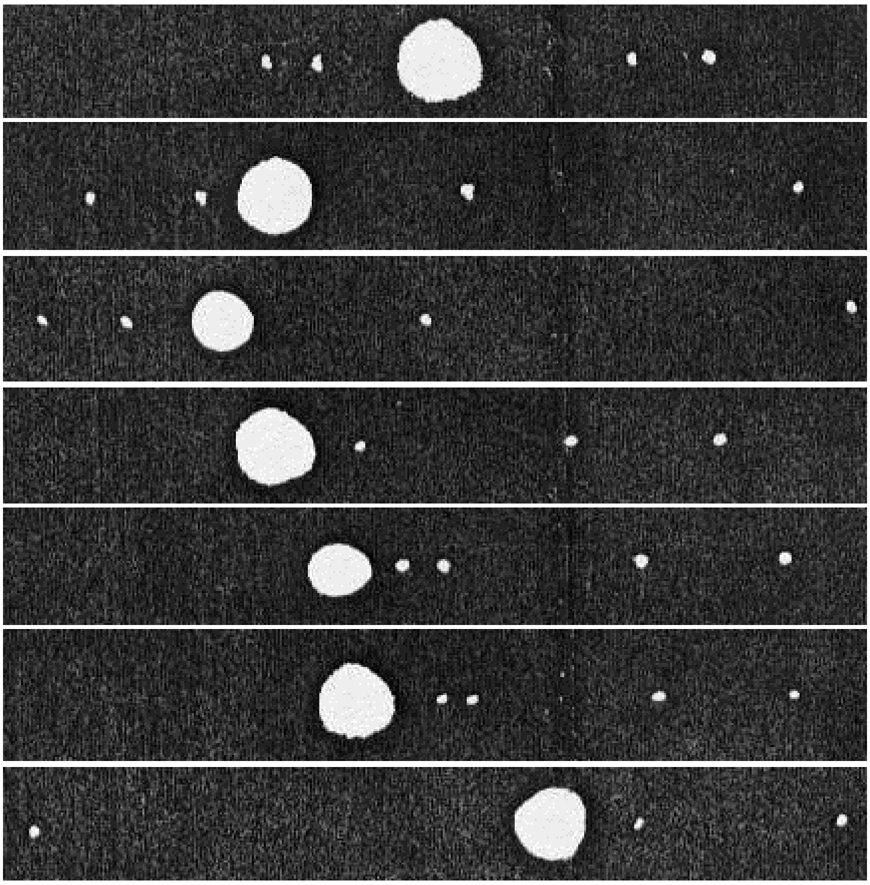

Figure 4. Galilean Satellites of Jupiter

• Activity 1: Calculating periods and orbital radius for one of the Galilean satellites of Jupiter

We assume that all Galilean satellites follow circular orbits turning round Jupiter. First of all we compute the radius of their orbit in each case.

To carry out this calculation we establish a proportion between real values of the orbit radius **a,** and the Jupiter´s real radius, and the measurements over the photograph of the furthest position of the satellite in respect to the planet $\mathbf{r_o}$, and its radius **R** (Figure 4).

When the satellite rotates round Jupiter its positions change. In particular, in Figure 5, their positions pass through **P', P'', Po, P'''** and so on, where the furthest position of the satellite is the **Po** position, so, the distance from this position to the centre will be the orbit's radius $\mathbf{r_o}$.

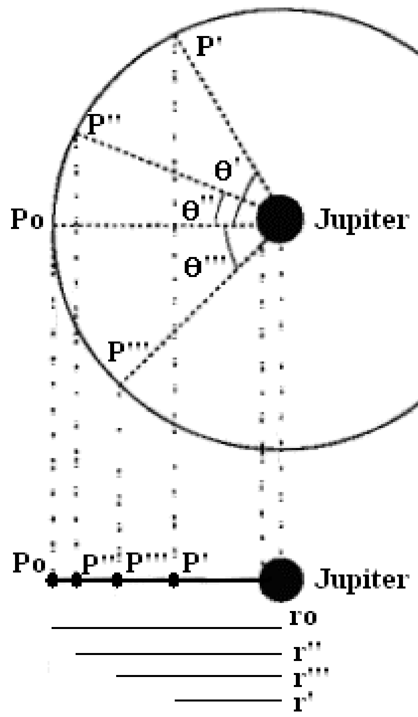

Figure 5. Relative position of the Satellite and Jupiter

For a specific satellite, we select from among all the collection of photographs where the position of the satellite is furthest from the planet. This distance, in centimetres, will be the radius of the orbit $\mathbf{r_o}$. It is not possible to measure the radius of Jupiter, **R,** from the image in the photographs 1, because the image of the planet is overexposed, so we have to measure using another photograph (Figure 6) taken using a shorter exposure time.

If we assume that the Jupiter radius is known to be 71000 km, we deduce that:

$$a = 71000\ r_o / R$$

where **a** is the real radius of the satellite orbit (in km), $\mathbf{r_o}$ is the radius of the orbit or else the maximum distance between the satellite and the planet in all the photographs (in cm) and **R** is the radius of Jupiter not overexposed (in cm).

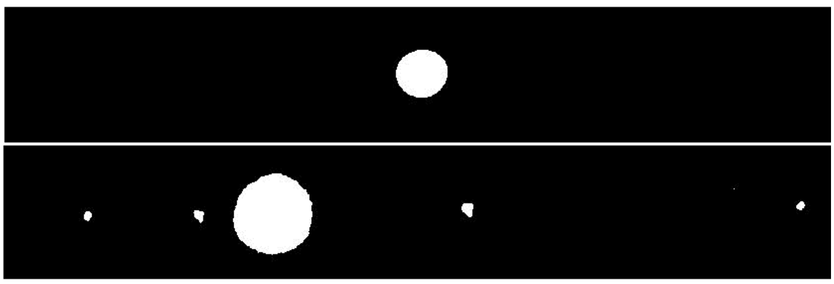

Figure 6. In the second image Jupiter appears deliberately overexposed in order to photograph its satellites. In the first image Jupiter is not overexposed in order to measure its radius

It is possible to repeat this process for each satellite, but we only suggest doing it for Io because is the quickest satellite and this means that with the same number of photos, really we have more useful observations.

From the set of photographs (Figure 4) we deduce the periods of Io. For this satellite, we study the link between the gap of time relating to the two photographs and the central angle of its orbit between both positions. The two positions of the satellite which we have to take into account must be different to $\mathbf{P_o}$, because this is corresponding to the maximum distance from the satellite to the planet.

For these positions **P', P''** or **P'''** (Figure 4), their respective central angles are not null and can be deduced in the following way

$$\theta' = \arccos (r' / r_o)$$

$$\theta'' = \arccos (r'' / r_o)$$

$$\theta''' = \arccos (r''' / r_o)$$

where **θ', θ'', θ'''** are the central angle (in degrees), **r', r'', r'''** are the distance from the satellite to the planet for each case (in cm) and $\mathbf{r_o}$ is the maximum distance to the planet from among all the observations (in cm).

For each position **P', P''** or **P'''** we know the exact moment **t', t''** or **t'''** respectively in which photographs were taken.

It is necessary to study them separately if the two positions of the satellite are both anterior or both posterior to the position **Po** in the photographs. Otherwise, one of these positions is anterior and the other one which is posterior. In the Figure 3, the first case is represented by positions **P'** and **P''** and the last case corresponds to positions **P'** and **P'''**.

If we consider the satellite moving from **P'** to **P''** (Figure 5), the interval of time passed is **t''-t'** and the covered angle is **θ'' - θ'**. Therefore making use of a simple proportion, the period of revolution of the satellite is:

$$P = 360\ (t''-t')/\ (\theta''-\theta')$$

where **P** is the period of revolution of the satellite (in days), **t', t''** are the time corresponding to two photographic observations, both anterior or both posterior to the maximum position **Po** (days) and **θ', θ''** are respective central angles of the two photographic observations, both anterior and both posterior to the maximum position $\mathbf{P_o}$ (degrees).

If the satellite is moved from **P'** to **P'''** (Figure 5), the interval of time passed is **t'''-t'** but the covered angle is now **θ'''+ θ'**. Then we can express the period by:

$$P = 360\ (t'''-t')/\ (\theta'''+\theta')$$

where **P** is the period of revolution of the satellite (in days), **t', t''** are the time corresponding to two photographic observations, one anterior and the other one posterior to the maximum position $\mathbf{P_o}$ (days) and **θ', θ''** are the respective central angles of the two photographic observations, one anterior and the other one posterior to the maximum position $\mathbf{P_o}$ (degrees).

We obtain this period using several photographs (Figure 4). It is convenient to repeat the method again with other photographs and finally to calculate the medium of all values obtained. We proceed in the same way for each one of satellites and we obtain the radius **a** of the Io orbit and its orbital period **P** (with the pictures included in this paper we obtained **a** = 6 R = 426000 km and **P** = 1.98 days, but the real values are **a**= 5.9 R and **P**= 1.77 days).

- Activity 2: Calculating the Jupiter mass

Making use of previous results and the third of Kepler's laws, we can determinate the mass of Jupiter M_J. It is well known that $\mathbf{a^3/ P^2 = const}$ and we can demonstrate that this constant is the mass of Jupiter expressed in solar mass. If we consider the satellites' movement around Jupiter in a circular orbit which radius is **a**, we can write

$$m\, v^2/a = G\, M_J\, m / a^2$$

For this circular movement, the speed **v** verify, $\mathbf{v^2 = G\, M_J / a}$. The period **P,** for a circular movement, is $\mathbf{P= 2\, \pi\, a/v}$, if we introduce the previous value of speed **v**:

$$P^2 = 4\, \pi^2\, a^3/ (G\, M_J)$$

And, for each satellite, it can be isolated using the third of Kepler's laws,

$$a^3/ P^2 = (G\, M_J)/ (4\, \pi^2)$$

If we write the previous relationship for the Earth around the Sun, using P=1 year and a=1 UA, we deduce the following equation

$$1 = (G\, M_S)/(4\, \pi^2)$$

If we divide the last two relationships, and using the solar mass as a unit to measure the mass of Jupiter, we obtain

$$a^3/ P^2 = M_J$$

where we know the orbital radius **a** (in AU), the period of revolution **P** (in years) and we can determine Jupiter's mass $\mathbf{M_J}$ (in solar mass units).

In the following, we will use values calculated before (to be noted in Table 1) in order to compute the mass of Jupiter. We will use the previous formula by changing the units of their members. First at all, we take into account that 1 AU is equivalent to 150 million km and expressing the period in days,

$$\mathbf{M_J = 0{,}0395 \times 10^{-18}\ a^3/ P^2}$$

where **a** is the orbit' radius of satellite (in km), **P** is the period of revolution of satellite (in days) and $\mathbf{M_J}$ is the of Jupiter (in solar masses).

In particular we can use this formula with the values calculated previously for Io (in our case $\mathbf{M_J}$ = 0.0008 solar mass in concordance with the real value $\mathbf{M_J}$ = 0.001 solar mass).

MODELS OF EXOPLANETARY SYSTEMS

The number of planets discovered outside Solar System is 340 (data of mid-February 2009) distributed in 289 planetary systems. They are called *exoplanets* and, with few exceptions all they are big, more massive than Jupiter which is the biggest planet in our Solar System. This is the reason why extra-solar planets masses are often compared with Jupiter mass ($1{,}9\times10^{27}$ kg). Only few of them are similar size like the Earth. The reason is due to technological limitations.

In this paper we will consider planetary systems with multiple planets. There are 36 planetary systems with more than 2 planets and only 12 with more than 3 planets. They will be topic of our discussion.

The nomenclature for exoplanetes is simple. A lowercase letter is placed after the star name starting by "b" for the first planet found in the system (p.e. 51 Pegasi b). The next planet found in the system could be labelled with the next letter in the alphabet c, d, e, f, etc. (51 Pegasi c, 51 Pegasi d, 51 Pegasi e or 51 Pegasi f).

Currently we know that there are exoplanets in different kind of stars. In 1992 radio astronomers announced the discovery of planets around the pulsar PSR 1257+12. This detection is considered the first definitive discovery of exoplantes. In 1995 was announced the first detection of exoplanets around the G-type star 51 Pegasi and after that had been detected exoplanets orbiting: a red dwarf star (Gliese 876 in 1998), a giant star (Iota Draconis in 2001), a brown dwarf star (2M1207 in 2004), a K-type star (HD40307 in 2008) and several months ago an A class star (Fomalhaut in 2008).

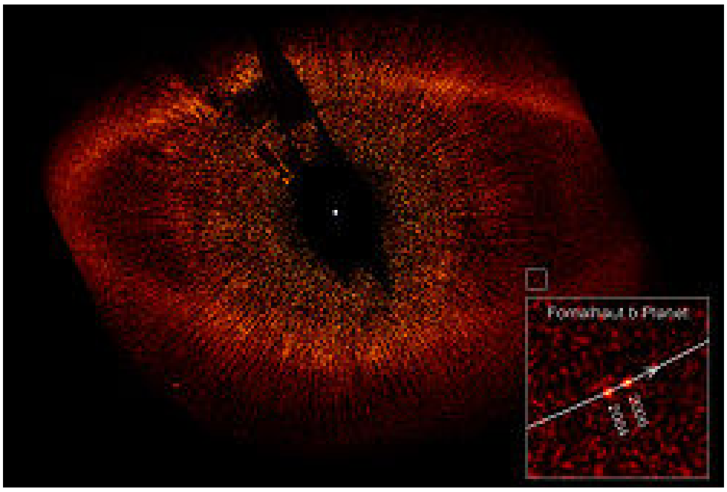

Figure 7. Planet Fomalhaut b inset against Fomalhaut's interplanetary dust clouds imaged by the Hubble Space Telescope's coronagraph (NASA photo)

Table 1. Extra-solar systems with multiple planets (three and more) Data taken from *Extra-solar Planets Catalog*[2] (except last column). When exploring the table you can find that some exoplanets are very close to the central star (Gliese 876 b, c and d orbits closer to the star than Mercury is to the Sun). Others of them have planets more far away (HD 69830 has a planetary system with three planets more or less far away than Neptune is to the Sun). One of the possibilities to visualize these data is to build scale models of chosen planetary systems. This will allow us easily to compare them with each other and with our Solar System.

Planet name	*Mean distance*, AU	*Orbital period*, days	*Minimum mass**, Jupiter masses	*Discov.* year	*Approximate diameter***, km
Gliese 876 d	***0,021***	***1.938***	***0,018***	***2005***	
Gliese 876 c	***0,13***	***30,1***	***0,56***	***2000***	
Gliese 876 b	***0,208***	***61,94***	***1,935***	***2000***	
55 Cnc e	0,038	2,817	0,034	2004	
55 Cnc b	0,115	14,651	0,824	1996	
55 Cnc c	0,24	44,345	0,169	2002	
55 Cnc f	0,781	260	0,144	2007	
55 Cnc d	5,77	5218	3,835	2002	
HD 40307 b	***0,047***	***4,312***	***0,013***	***2008***	
HD 40307 c	***0,081***	***9.62***	***0,022***	***2008***	
HD 40307 d	***0,134***	***20.46***	***0,029***	***2008***	
Ups And b	0,059	4,617	0,69	1996	~Júpiter 124000
Ups And c	0,83	241,52	1,98	1999	~Júpiter 176000
Ups And d	2,51	1274,6	3,95	1999	~Júpiter 221 000
Gl 581 b	***0,041***	***5,368***	***0,049***	***2005***	***Terrestrial 32000***
Gl 581 c	***0,073***	***12,932***	***0,016***	***2007***	***Terrestrial 22000***
Gl 581 d	***0,25***	***83,6***	***0,024***	***2007***	***Terrestrial 2507000***
HD 69830 b	0,079	8,667	0,033	2006	
HD 69830 c	0,186	31,56	0,038	2006	
HD 69830 d	0,63	197	0,058	2006	
HD 181433 b	***0,08***	***9,374***	***0,024***	***2008***	
HD 181433 c	***1,76***	***962***	***0,64***	***2008***	
HD 181433 b	***3***	***2172***	***0,54***	***2008***	
HD 160691 d	0,09	9,55	0,044	2004	
HD 160691 e	0,921	310,55	0,522	2006	
HD 160691 b	1,5	654.5	1,67	2000	
HD 160691 c	4,17	2986	3,1	2004	
PSR 1257+12b	***0,19***	***25,262***	***0,00007***	***1992***	
PSR 1257+12c	***0,36***	***66,542***	***0,013***	***1992***	
PSR 1257+12d	***0,46***	***98,211***	***0,012***	***1992***	
HD 74156 b	0,294	51,65	1,88	2003	
HD 74156 d	1,01	336,6	0,396	2007	
HD 74156 c	3,85	2476	8,03	2003	
HD 37124 b	***0,53***	***154,46***	***0,61***	***1999***	
HD 37124 d	***1,64***	***843,6***	***0,6***	***2002***	
HD 37124 c	***3,19***	***2295***	***0,683***	***2005***	
HD 8799 d	24	36500	10	2008	
HD 8799 c	38	69000	10	2008	
HD 8799 d	68	170000	7	2008	

* Method of radial velocities gives only minimum mass of the planet

** The diameter which appears had been calculate assuming that the planet density equals Jupiter density (1330 kg/m^3) or when we consider the planet as a possible terrestrial exoplanets. In this case the diameter had been calculated using planet density equals Earth density (5520 kg/m^3).

Table 2. Solar System planets

Planet name	*Mean distance*, AU	*Orbital period*, years	*Mass*, Jupiter masses	*Diameter*, km
Mercury	0,3871	0,2409	0,0002	4879
Venus	0,7233	0,6152	0,0026	12 104
Earth	1,0000	1,0000	0,0032	12 756
Mars	1,5237	1,8809	0,0003	6794
Jupiter	5,2026	11,8631	1	142 984
Saturn	9,5549	29,4714	0,2994	120 536
Uranus	19,2185	84,04	0,0456	51 118
Neptune	30,1104	164,80	0,0541	49 528

• Activity 3: Determination of exoplanet's diameter.

At first we will calculate the diameter of a couple of exoplanets included in Table 1. It is simple to do it if we know the density of the planet (assuming it is equal to Jupiter density or Earth density for terrestrial exoplanets. By definition, the density verify **ρ = m/ V**.

The mass **m** of the exoplanet appears in Table 1, and the volume **V** can be obtained considering the planet as a sphere $V = 4\pi R^3/3$ If we substitute this formula in the previous one, the radius R can be obtained:

$$R = \sqrt[3]{3m / (4\pi\rho)}$$

We propose to the readers that they calculate the diameter of Gliese 581d (the terrestrial exoplanet) assuming $\rho = 5520$ kg/m^3 (Earth's density). The result expected appears in Table 1. Repeat the calculations for a non-terrestrial exoplanet. For instance, the first multiple-planetary system to be discovered around a main sequence star was Upsilon Andromedae. It contains three planets, all of which are Jupiter-like: planets Ups b, c and d. Calculate the diameter of them assuming $\rho = 1330$ kg/m^3 (Jupiter's density) and compare the result with Table 1.

Using this results and the mean distance which appears in Table 1, you can produce a model in the next section.

• Activity 4: Determination of parent star's mass

In a similar way that we calculated the mass of the parent star of each exosystem by means of Io in the first part of this paper, we can calculate the mass of the central star of an exoplanet system.

$$M_S = 0{,}0395 \times 10^{-18}\ a^3/ P^2$$

where **a** is the orbit' radius of exoplanet (in km), **P** is the period of revolution of satellite (in days) and $\mathbf{M_S}$ is the mass of the parent star (in solar masses).

For instance calculate the mass of the parent star of Ups And and Gl 581 in solar mass (the result should be 1.03 solar mass).

- Activity 5: Scale model of exoplanetary systems

Let's choose the scale of the model. For distance the appropriate scale is: **1 AU = 1 m**. In this case all exoplanets can be put in a typical classroom and also the first five planets of our Solar System (including Jupiter) can be shown. If the activity is performed outside (for example in schoolyard) a complete model can be built. As regard the planet size different scale must be used, for example: **10 000 km = 1 cm**. In this case the largest planet, Jupiter, will be 11 cm in diameter and the smallest planet Mercury 0.2 cm size.

We can now build the solar system, the Upsilon Andromedae system and the Gliese 581 system using the values of mean distance included in Table 1 and the diameters calculated before. It is also a good idea to make other exoplanetary systems that appear in Table 1 if we calculate at first their diameters.

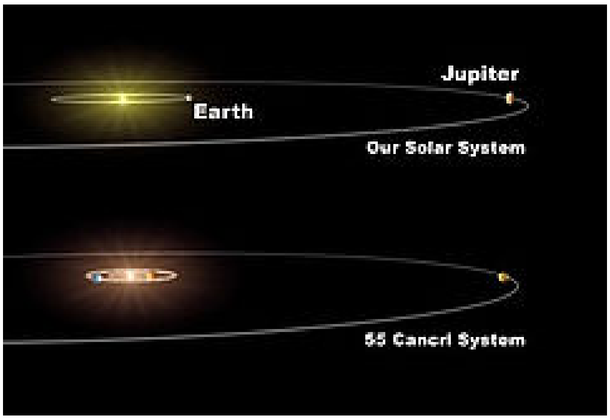

Figure 8. Our own Solar System and 55 Cancri System

Many exoplanets orbit much closer around their parent stars than any planet in our own solar system orbits around the Sun. Many planets are closer to their parent star than Mercury in Solar System. This means that they are very hot. Another difference is that many large planets are close to their stars. Inner part of Solar System is occupied by small rocky planets and first gas giant (Jupiter) is placed 5,2 AU from the Sun. This is mainly an observational selection effect because the radial velocity method is more sensitive when the planets are in such small orbits. But it is clear to think now that most exoplanets have much larger orbits. It is appears plausible that in most exoplanets systems, there are one or two giant planets with orbits comparable in size to those of Jupiter and Saturn in our own Solar System.

Now let's think about possible habitability of exoplanets. Approximate calculations show that habitable zone in Solar System where liquid water can exist (temperature range from 0 to 100 °C) extends from 0,56 to 1,04 AU[3]. Inner border of this zone is between orbits of Mercury and Venus and outer border is just outside the Earth orbit. Only two Solar System planets; Venus and Earth are inside habitable zone (Figure 9). As we know only the Earth is inhabited, Venus is too hot (but only because of very strong greenhouse effect on this planet). Currently, Gliese 581d appears as the best example yet discovered of a possible terrestrial exoplanet that orbits close to the habitable zone surrounding the parent star. And Gliese 581 d appears as a potential candidate for extraterrestrial intelligence. Gliese 581 c begins in a position that might be within the host star's habitable zone. It has been determined that this exoplanet could support liquid water and the possibility of life. It would allow for water to exist in its liquid state and it looks impossible because some studies indicate that this planet most likely suffers from a runaway greenhouse effect similar to Venus.

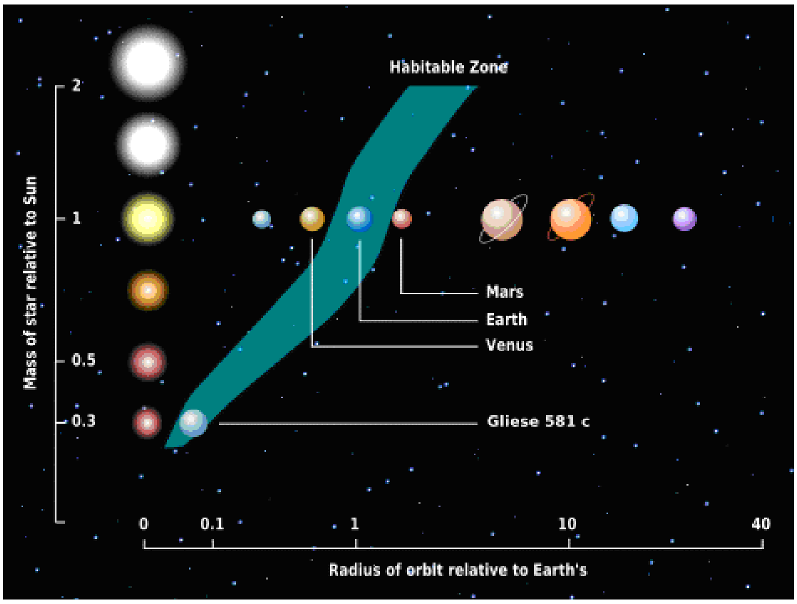

Figure 9. Planetary habitability figure shows where life might exist on exoplanets in our own solar system and life on Earth

There are still many unanswered questions about the proprieties of exoplanets. The recent discovery that several surveyed exoplanets lacked water means that there is still much more to be learns about their proprieties.

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